Global methane emissions from landfills: New methodology and annual estimates 1980–1996

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[1] Significant interannual variations in the growth rate of atmospheric CH_4 justify the development of an improved methodology for landfill emissions, the largest anthropogenic source in many developed countries. A major problem is that reliable solid waste data often do not exist, especially for developing countries where emissions are increasing. Here we develop and apply a new proxy method to reconstruct historical estimates for annual CH_4 emissions for the period 1980–1996. Using composited solid waste data from 1975–1995, we developed linear regressions for waste generation per capita based on energy consumption per capita, a surrogate which reflects population and affluence, the major determinants of solid waste generation rates. Using total population (developed countries) or urban population (developing countries), annual landfill CH_4 emissions were estimated using a modified Intergovernmental Panel on Climate Change (IPCC) methodology. Methane recovery was modeled by fitting historic data to time-dependent linear relationships. Two scenarios for global emissions using the surrogate were compared to two scenarios using an IPCC standard methodology. Results from all four scenarios range from 16 to 57 Tg CH_4 yr^{-1}, a similar range as previous estimates. We support the use of the lower energy surrogate scenario (A) with annual emissions of 16–20 Tg CH_4 yr^{-1}, both positive and negative annual variations, and commercial recovery >15% by 1996. The surrogate provides a reasonable methodology for a large number of countries where data do not exist, a consistent methodology for both developed and developing countries, and a procedure which facilitates annual updates using readily available data. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1620 Global Change: Climate dynamics (3309); 1694 Global Change: Instruments and techniques; *KEYWORDS:* landfill, landfill gas, methane emissions, methanotrophy, methanogenesis

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1. Introduction

[2] Methane (CH_4) is an important greenhouse gas: the total positive climate forcing attributed to CH_4 over the last 150 years is 40% that of carbon dioxide [*Hansen et al.*, 1998]. Moreover, CH_4 has a relatively short atmospheric lifetime of about 10 years, so that changes in CH_4 sources can affect atmospheric concentrations on decadal or shorter timescales. In situ measurements of atmospheric CH_4 since 1983 [*Steele et al.*, 1987] show large interannual variations and a declining growth rate after 1990 [*Dlugokencky et al.*, 1994, 1998, 2001]. The atmospheric CH_4 burden grew by 25–40 Tg yr^{-1} in the 1980s (1 Tg = 10^{12} g) and at a slower rate of <20 Tg yr^{-1} during the 1990s, except for higher rates in 1991 and in 1998 [*Dlugokencky et al.*, 2001]. Although climate-related variations in wetland emissions can explain most of the large annual anomalies [*Walter et al.*, 2001], the cause of the declining growth rate during the 1990s is not understood. The major sink for atmospheric CH_4 is reaction with tropospheric OH. Methane oxidation by methanotrophic microorganisms in aerated soils provides an additional smaller sink. Since the atmosphere reflects the net balance of all sources and sinks, any changes in the growth rate must be the result of changing sources, changing sinks, or both. Methodologies are needed to quantitatively address these changes on an annual basis.

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[3] Deciphering the interannual to decadal dynamics of the global CH_4 cycle requires an understanding of the temporal behavior of individual sources and sinks. Terrestrial CH_4 sources include natural wetlands, rice production, ruminant animals, termites, wastewater treatment, fossil fuel production and consumption, biomass burning, and landfills [*Khalil*, 2000]. The non-wetlands sources collectively account for more than half of the annual atmospheric input of 450–550 Tg [*Matthews*, 2000], and there is considerable uncertainty with respect to their individual magnitude and short-term variability.

[4] This is especially true for landfills: global CH_4 emissions estimates have ranged from 9 to 70 Tg yr^{-1} [*Bingemer and Crutzen*, 1987; *Richards*, 1989]. Estimates are based on measured or estimated national solid waste generation, the fraction landfilled, the fraction landfilled that is expected to biodegrade anaerobically, the degradable organic carbon (DOC) content of that fraction, and the CH_4 content of the biogas product; for some developed countries, subtractions are made for methanotrophic CH_4 oxidation in cover soils and CH_4 recovery via pumped systems (see section 3.1). In general, solid waste data are lacking for many countries, the reliability of existing data for many countries is questionable, and, because steady state assumptions are applied to solid waste generation, interannual variability is not well quantified. Moreover, the wide range of observed emission and oxidation rates (more than 7 orders of magnitude [*Bogner et al.*, 1997a]) exacerbates the problem of calculating national and global emissions. Unlike some of the other CH_4 sources, there have been no regional multiyear field campaigns for landfill emission measurements; thus empirical or semi-empirical models based on latitude and climate do not currently exist which are capable of predicting seasonal emissions inclusive of oxidation.

[5] In this paper we present and apply a new proxy method to reconstruct historical estimates for annual global CH_4 emissions from landfills for the period 1980–1996. This study was part of a broader effort to better assess short-term CH_4 emissions from several sources. The current study relies on calculated annual per capita solid waste generation based on a surrogate variable (per capita energy consumption) and the application of a modified IPCC methodology. Section 2 provides background on the processes of CH_4 production, oxidation, and emission at landfills and an assessment of current measurements, data, and models; section 3 describes the data and methodology used in the study; section 4 provides regional and global results for solid waste generation and historical CH_4 emissions; and section 5 concludes with recommendations for IPCC, remaining data needs, and suggestions for future research. This study addresses several current weaknesses in the global estimates by explicitly considering all of the following: short-term temporal variations in per capita waste generation, influences of controlled landfilling, quantification of engineered CH_4 recovery, and inclusion of aerobic microbial CH_4 oxidation. In future work, as more field measurements become available, the development of improved empirical models for landfill CH_4 emissions at national scales will become feasible.

2. Background

2.1. Processes, Terminology, and Current Understanding

[6] Landfill CH_4 emissions are controlled by the amount and composition of landfilled waste; the anaerobicity and CH_4 yields achieved by engineering design and landfill management practices; the composition and thickness of cover materials; and the installation of engineered gas extraction systems for landfill CH_4 recovery.

2.1.1. Methane Generation: Anaerobic Production From Biodegradable Waste

[7] When solid waste is buried in a landfill, the biodegradable fractions decompose via a complex series of microbial reactions under anaerobic conditions. These fractions include readily degradable food waste, more slowly degradable paper (cellulosic) wastes, and garden or commercial wastes containing slow to rapidly degradable components. In developed countries, landfilled solid waste typically contains total biodegradable components of 60–75% (w/w) with degradable organic carbon (DOC) of approximately 15–25% (w/w) [*Bingemer and Crutzen*, 1987]. (Note that DOC refers to ''degradable organic carbon'' in this paper to be consistent with IPCC terminology.) Major intermediate products during decomposition include acetic acid (CH_3COOH), other carboxylic acids, carbon dioxide (CO_2), and hydrogen (H_2). The terminal reaction is the production of CH_4 by methanogenic microorganisms via acetate cleavage or reduction of CO_2 with H_2. As a result of these two pathways, landfill gas consists of 50–60% CH_4 (v/v) with the remainder primarily CO_2 [*Bogner et al.*, 1996]. In developing countries, most solid waste disposal occurs at non-engineered sites without soil cover where a large fraction of the DOC may decompose aerobically to CO_2 rather than degrade anaerobically to CH_4. However, empirical evidence confirms that CH_4 generation does occur at such sites after older waste is buried with younger waste, especially in humid climates.

[8] If decomposition reactions proceed at optimized rates, then the mass of CH_4 produced depends directly on the mass of DOC landfilled, i.e., the waste composition. *Bingemer and Crutzen* [1987], in the first global estimate of landfill CH_4 emissions, assumed that 0.77 of the landfilled DOC was ''dissimilated,'' that is, anaerobically converted to biogas carbon (CH_4 and CO_2). This was based upon a temperature-dependent equation for optimized low-solids anaerobic decomposition and, using a typical waste DOC composition for developed countries, was equivalent to a CH_4 yield of 0.10 kg CH_4 kg^{-1} (dry) solid waste. The theoretical maximum CH_4 yield, based upon an empirical equation for U.S. solid waste composition, is approximately 0.18 kg CH_4 (dry) kg^{-1} solid waste [*Halvadakis et al.*, 1983]. In contrast, optimized laboratory studies of solid waste decomposition from the United States, Germany, and Italy have shown that the dissimilated DOC fraction ranges from negligible to a maximum of 0.25–0.47 [*Bogner and*

Spokas, 1993, Table 4], which is equivalent to maximum yields of 0.04–0.08 kg CH_4 kg^{-1} (dry) solid waste.

[9] Methane yields in field settings are lower because landfills do not function as efficiently as anaerobic digesters or laboratory systems. Indeed, *Richards* [1989] assumed a yield of 0.036 kg CH_4 kg^{-1} (dry) solid waste, based on commercial landfill CH_4 recovery data. Some recent literature has proposed CH_4 yields ranging from 0.07 to 0.13 kg CH_4 kg^{-1} (dry) solid waste [*Kura and Lee*, 1995; *Li et al.*, 1999]; note that the higher figure exceeds that used by *Bingemer and Crutzen* [1987].

[10] A major issue is proportioning the CH_4 yield over the 20–30 year time period during which most of the anaerobic decomposition is expected to occur. To date, all global estimates have incorporated steady state assumptions for CH_4 generation based on current waste disposal quantities; this assumes instantaneous CH_4 generation from landfilled solid waste. It is well known that, in engineered landfills in developed countries, CH_4 generation can begin within a few weeks of burial. Thus this approach is reasonable for global estimates, since national annual CH_4 production cannot be more precisely defined for many countries.

[11] In many developed countries, a more sophisticated approach is followed for national landfill CH_4 generation as the basis for emissions reported to IPCC: a first-order kinetic equation is used to calculate landfill gas production from the quantity of solid waste landfilled in single years integrated with the CH_4 production from solid waste landfilled in previous years. This approach presumes that the quantity and composition of landfilled waste as well as a rate constant can be reasonably well-defined. Depending on the form of the equation used, the optimum rate of production from a particular mass of landfilled waste occurs some years after burial, then rates decline and tail off for more than two decades. The first-order kinetic equations are similar to those used for individual commercial landfill CH_4 recovery projects where it is important to match recovery hardware to projected gas quantities. These approaches have been validated in site-specific studies where detailed waste input data were available. The most comprehensive study of this type was completed in the Netherlands during the 1990s. A series of first-order generation equations (single component to multicomponent with respect to waste composition) were compared to actual gas production at nine landfills with well-defined waste composition, concluding that a multicomponent model best predicted rates ±30% of actual CH_4 generation [*Coops et al.*, 1995; *Oonk et al.*, 1993; *Scheepers and van Zanten*, 1994]. Recently, a uniform kinetic model has been applied to gas generation from all landfills in Canada [*Conestoga-Rovers & Associates and The Delphi Group*, 1999].

[12] Both the first-order kinetic approach (termed Tier 2 first-order decay (FOD) method) and the calculation of CH_4 emissions from annual solid waste disposal quantities (termed Tier 1 method) are approved IPCC methods [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. In practice, developed countries tend to apply the FOD methods while developing countries rely on Tier 1 methods.

[13] For the United States, there are three annual landfill CH_4 emissions estimates beginning in 1990: (1) official IPCC estimates by the U.S. Environmental Protection Agency (EPA) [*U.S. Environmental Protection Agency* (*EPA*), 2002]; (2) estimates by the U.S. Department of Energy/Energy Information Agency (DOE/EIA) [*U.S. DOE/EIA*, 2001]; and (3) estimates by the *U.S. EPA/Office of Policy* [1999]. For 1990–1999, these report net emissions inclusive of gas recovery ranging between 8.5 and 12 Tg yr^{-1} with three different trends: The *U.S. EPA* [2002] emissions increase, then decrease and level off; the *U.S. DOE/EIA* [2001] emissions decrease; and the *U.S. EPA/Office of Policy* [1999] emissions increase (1990–1996 only). The *U.S. DOE/EIA* [2001] estimate includes subtractions for recovery of 1–2.5 Tg yr^{-1} for the 1990–1996 period, including both flaring and commercial recovery with the latter referenced to a database maintained by the U.S. EPA/LMOP (Landfill Methane Outreach Program) (E. Scheele, U.S. EPA, personal communication, 2002). The *U.S. EPA* [2002] estimates higher 1996 recovery of 3.2 Tg while the *U.S. EPA/Office of Policy* [1999] estimates level recovery of 1.5–2.0 Tg for 1990–1996. The reader is referred to the references cited above for the assumptions and calculations that led to these differences. It is important to note that an FOD method is used only for the estimates in *U.S. DOE/EIA* [2001]. The *U.S. EPA* [2002] IPCC estimates rely on a linear regression to calculate CH_4 production per unit time from the mass of waste in place [*Peer et al.*, 1993; *U.S. EPA*, 1993], assume 10% CH_4 oxidation, use numbers for commercial recovery from the EPA/LMOP database, and supplement the latter with an estimate for gas that is recovered and flared at sites without commercial recovery.

2.1.2. Methane Mass Balance

[14] Once CH_4 is produced in a landfill, direct emission to the atmosphere via diffusive and convective flux mechanisms is one possible pathway. Methane may also be oxidized to CO_2 in aerobic cover soils, recovered by active gas extraction systems, temporarily retained within the landfill volume, or migrated laterally in the subsurface. Lateral migration through layered strata should be negligible at well-controlled sites; however, data confirm that migration can occur to distances of >300 m [*Kjeldsen*, 1996]. This mass balance relationship is summarized in the following equation [*Bogner and Spokas*, 1993]:

$$\begin{aligned} CH_4\ \text{Production} = {} & CH_4\ \text{Emitted} + CH_4\ \text{Oxidized} \\ & + CH_4\ \text{Recovered} + \text{Lateral}\ CH_4\ \text{Migration} \\ & + \Delta CH_4\ \text{Storage} \left[\text{all units} = \text{mass time}^{-1}\right]. \end{aligned} \quad (1)$$

2.1.3. Methane Recovery

[15] At sites with active gas extraction systems using vertical wells or horizontal collectors, a large percentage of the gas may be recovered. The first commercial recovery of landfill CH_4 occurred in 1975 at the Palos Verdes Landfill in southern California. Landfill CH_4 is currently being used to fuel industrial boilers; to generate electricity using internal combustion engines, gas turbines, or steam turbines; and to produce a substitute natural gas after removal of carbon dioxide and trace components. There are currently more than 300 such commercial projects in the United States, most of which generate electricity on-site

using internal combustion engines or gas turbines. *Meadows et al.* [1996] estimated that there were more than 500 commercial projects worldwide in 1995, and unofficial estimates suggest that more than 900 plants exist today. At many sites where commercial utilization is not economically feasible, the recovered CH_4 is flared. The majority of developed countries target landfill CH_4 recovery as a greenhouse gas mitigation mechanism because it is a major anthropogenic source that can be readily controlled by active recovery systems. Moreover, because engineered landfills in developed countries are already subject to regulatory programs requiring gas control to prevent the formation of explosive CH_4/air mixtures, additional regulations mandating recovery for some or all sites can be readily implemented.

[16] Although the mass of CH_4 produced, oxidized and emitted in a particular year is dependent on waste quantity, years in place, climate, landfill design, and management factors, CH_4 recovery is probably the single most important factor influencing emissions. Through a combination of intensive field measurements, supporting laboratory studies, and modeling, the CH_4 mass balance has been recently quantified at two French landfills [*Diot et al.*, 2001]. At Montreuil-sur-Barse in eastern France (near Troyes), only about 1–2% of the CH_4 production is being emitted and about 97% is being recovered in a cell with an active gas extraction system. At Lapouyade (near Bordeaux in southwestern France), a minimum of 94% of the CH_4 production is being recovered at two cells with engineered gas recovery. In contrast, for a cell without recovery, 92% of the CH_4 production is being emitted. The measured recovery of >90% for the French studies is higher than the 60–80% often assumed for commercial projects, suggesting that gas generation models may be overestimating gas production, resulting in a lower % recovery when applied to an inflated generation.

2.1.4. Methane Oxidation

[17] Methane oxidation is accomplished by methanotrophic microorganisms in cover soils and can range from negligible to 100% of internally produced CH_4; under some circumstances, atmospheric CH_4 may be oxidized at the landfill surface [*Bogner et al.*, 1995, 1997b, 1999; *Borjesson*, 1996; *Borjesson and Svensson*, 1997]. The thickness, physical properties, and moisture content of cover soils directly affect CH_4 oxidation, because rates are limited by the transport of CH_4 upward from anaerobic zones and O_2 downward from the atmosphere. In recent French mass balance studies [*Diot et al.*, 2001], a stable carbon isotopic technique [*Chanton and Liptay*, 2000] demonstrated that CH_4 oxidation was negligible at Montreuil-sur-Barse during cold, wet winter conditions. At Lapouyade, 15% oxidation was observed during a winter field campaign under warmer Mediterranean conditions. *Chanton and Liptay* [2000] have previously shown that seasonal variations in fractional CH_4 oxidation at a Florida landfill may range from negligible to >40%. Oxidation rates in conventional landfill cover soils may be as high as 166–240 g CH_4 m^{-2} d^{-1} [*Knightley et al.*, 1995; *De Visscher et al.*, 1999] and greater than 1000 g m^{-2} d^{-1} in thick, compost-amended covers engineered to optimize oxidation [*Humer and Lechner*, 2001]. Landfill soils can thus attain the highest rates of CH_4 oxidation recorded in the literature with rates many times higher than wetland settings but a similar coupling between anaerobic CH_4 generation and aerobic oxidation.

[18] At sites with engineered gas recovery resulting in low CH_4 fluxes to the atmosphere, field measurements have demonstrated that methanotrophs can consume all the CH_4 transported upward to cover soils and, additionally, oxidize atmospheric CH_4 [*Bogner et al.*, 1995, 1997b, 1999; *Borjesson and Svensson*, 1997]. Recent modeling for landfill settings has indicated that zero or negative emissions are possible only where low CH_4 gradients and threshold concentrations in soil gas are present, implying the presence of a pumped gas recovery system [*Bogner et al.*, 2000]. Thus the combination of engineered and natural controls on landfill CH_4 emissions can be extremely effective in reducing emissions.

2.1.5. Methane Emissions

[19] Emissions equal the gross CH_4 production reduced by oxidation, recovery, lateral migration, and partitioning to internal storage, as shown in equation (1). Results from a limited number of whole landfill CH_4 emissions measurements in Europe, the United States, and South Africa exhibit about 1 order of magnitude variation—from 0.1 to 1.0 tonnes CH_4 ha^{-1} d^{-1} (equivalent to 0.03 to 0.3 g CH_4 m^{-2} d^{-1}) [*Nozhevnikova et al.*, 1993; *Hovde et al.*, 1995; *Borjesson*, 1996; *Czepiel et al.*, 1996b; *Mosher et al.*, 1999; *Tregoures et al.*, 1999; *Galle et al.*, 2001; *Morris*, 2001]. Because detailed CH_4 mass balance data exist only for the French sites discussed above, previous estimates of global landfill CH_4 emissions have tended to focus on CH_4 production alone, with the exception of some developed countries where recovery and oxidation have been included in the bulk estimates. Thus the historical maximum and minimum CH_4 yields discussed above by *Bingemer and Crutzen* [1987] and *Richards* [1989] respectively, translate into the maximum and minimum global emissions estimates: 30–70 Tg CH_4 yr^{-1} [*Bingemer and Crutzen*, 1987] and 9–18 Tg CH_4 yr^{-1} [*Richards*, 1989]. In both cases, they relied on assumptions for the quantity of waste generated and landfilled combined with steady state CH_4 production, all of which was assumed to be emitted to the atmosphere. More recent studies have estimated intermediate values: 19–40 Tg yr^{-1} by *Doorn and Barlaz* [1995]; emissions for 1994 of 40.3 Tg by *Stern and Kaufmann* [1998]; emissions for 1995 of 43 Tg yr^{-1} by *Meadows et al.* [1996]; and combined 1990 emissions for landfills and sewage sources of 51–62 Tg by N. Nakicenovic et al.(Special Report on Emissions Scenarios, Intergovernmental Panel on Climate Change (IPCC), available at http://www.grida.no/climate/ipcc/emission/index.html, 2000).

2.2. Global Modeling and Data: Status, Issues, and Problems

[20] The IPCC develops methodologies to estimate greenhouse gas emissions for all countries and provides default values for required parameters if country-specific data are lacking. For landfill CH_4 emissions, as developed by IPCC

working groups [*IPCC*, 1996], a simplified mass balance equation is used for national estimates,

$$\mathrm{CH_4\ Production} = \Sigma(\mathrm{CH_4\ Emitted} + \mathrm{CH_4\ Oxidized} + \mathrm{CH_4\ Recovered})\left[\text{all units} = \text{mass time}^{-1}\right]. \quad (2)$$

[21] In practice, equation (2) is rewritten in terms of CH_4 emissions and applied by the IPCC as the Tier 1 default methodology for calculating CH_4 emissions from solid waste disposal. Methane production for each country is calculated from waste generation data (either measured or calculated) and the landfilled fraction decomposing anaerobically (termed the "CH_4 correction factor" by IPCC). Under current guidelines for emissions inventories, IPCC also encourages countries to use Tier 2 FOD (first-order decay) methods, as discussed above, if sufficient data are available.

[22] A basic weakness in most national estimates is the scarcity and poor quality of annual data for landfilled solid waste. For many countries, these data are highly uncertain and not referenced to a specific year. This is especially true for developing countries and the emerging economies of Asia, Africa, eastern Europe and the former USSR. Typically, for Tier 1 estimates, an estimated per capita waste generation is used with population statistics to calculate national solid waste generation. In many cases, the per capita waste generation estimates are extrapolated without statistical validation from (1) limited data for an urban area within a country where waste collection data exist or (2) data from a neighboring or similar country. Even in developed countries, solid waste data have often not been compiled or estimated using uniform methods [*Mertins et al.*, 1999]. For example, the "household" or "municipal solid waste" (MSW) collected by municipalities or regional authorities is typically used as the basis for this calculation. Depending on the country and the importance of landfilling as a solid waste disposal method, additional biodegradable waste streams may be landfilled that are not counted within the MSW; these may include commercial paper, non-hazardous commercial and industrial waste (including readily degradable food processing/restaurant waste), landscaping waste, and construction and demolition (C&D) debris. The inclusion of significant quantities of C&D debris, for example, which has a low biodegradation potential, would lead to an overestimate of CH_4 emissions.

[23] For the United States, there are two independent methods with differing results for solid waste generation and the fraction landfilled. The first relies on a commodities production and materials flow model initiated during the mid-1970s [*Franklin Associates*, 1999], while the second is an annual compilation of state statistics by Biocycle magazine for the mass of solid waste produced, recycled, and landfilled since 1990 [*Goldstein and Madtes*, 2001]. The Franklin and Biocycle data sets are not reconciled in the United States, although the Franklin estimates are annually commissioned by the U.S. EPA and considered the more official numbers. In general, the Biocycle totals are 35–55% higher than the Franklin totals because they include construction and demolition (C&D) debris for most states, plus commercial and industrial waste for many states. The Franklin numbers better approximate the municipal solid waste or household waste reported for European Union (EU) countries, where the C&D debris and other waste streams with lower CH_4 potential are reported separately. The 1990 landfilled fraction reported by Franklin was 0.68 compared to 0.84 for the Biocycle compilation. Between 1990 and 1996, both compilations reported declining landfilled fractions, to 0.56 for Franklin and to 0.63 for Biocycle [*Franklin Associates*, 1999; *Goldstein and Madtes*, 2001].

[24] With respect to estimates of CH_4 emissions from landfilled solid waste, it is also important to distinguish between science goals and regulatory goals. One issue that has arisen in the United States is that a mandatory emissions calculation for regulatory purposes at larger landfill sites uses a standardized FOD method which yields high generation rates with assumptions of no CH_4 oxidation and rates of recovery below 80% (Tier I calculations, U.S. EPA New Source Performance Standards). The goal is to bring a critical number of large sites into a national regulatory program. However, calculated emissions are biased on the high side and, at individual sites, an inflated benchmark is established against which subtractions for actual gas recovery result in unrealistically high residual emissions.

3. Methodology

3.1. Baseline IPCC Methodology (Tier 1)

[25] The simplified CH_4 mass balance given in equation (2) is rewritten in terms of CH_4 emissions and applied by the IPCC as the default methodology for calculating CH_4 emissions from solid waste disposal. Below we preserve the IPCC terminology, including some abbreviations with alternative meanings in the literature; for example, DOC refers to "degradable organic carbon," not "dissolved organic carbon." Annual national emissions are calculated according to the following default equation [*IPCC*, 1996]:

$$\mathrm{CH_4\ emitted}\left(\mathrm{Tg\ yr^{-1}}\right) = \{[(\mathrm{MSW_t})(\mathrm{MSW_f})(\mathrm{MC_f})(\mathrm{DOC}) \cdot (\mathrm{DOC_f})(\mathrm{F})(16/12)] - \mathrm{R}\}(1 - \mathrm{OX}), \quad (3)$$

where MSW_t = municipal solid waste (MSW) generated (Tg yr^{-1}), MSW_F = national fraction MSW disposed in engineered or non-engineered landfill, MC_F = landfilled fraction MSW which decomposes anaerobically (CH_4 correction factor:1.0 for developed countries), DOC = fraction biodegradable organic carbon in landfilled MSW, DOC_f = fraction DOC "dissimilated" (actually converted to CH_4 and CO_2 in landfill gas), F = fraction CH_4 in landfill gas (v/v) (default is 0.5), R = recovered CH_4 (Tg yr^{-1}) using an active extraction system, and OX = fraction CH_4 oxidized by methanotrophs (default is 0).

[26] Thus the landfill CH_4 generation by country is calculated from solid waste generation data (either measured or calculated), the landfilled fraction decomposing anaerobically (the CH_4 correction factor), the fraction DOC, the fraction of that DOC that is converted to landfill gas, and the volume fraction of CH_4 in the gas. Finally, sub-

tractions for CH_4 oxidation or CH_4 recovery yield the net CH_4 emissions. National estimates are summed to provide global estimates.

3.2. Proposed Revisions to IPCC Methodology, Including Use of Surrogate Variable

[27] Solid waste generation increases with rising population, but it is also statistically related to socioeconomic variables indicating general level of affluence [*Bogner et al.*, 1993]: richer societies generate more waste per capita. Since the existence and quality of solid waste generation data are highly variable among countries, it is desirable to use a surrogate variable for which uniform worldwide statistical data exist and which adequately represents annual per capita solid waste generation. Requirements for a surrogate are correlation with solid waste generation, availability of data for all countries, availability of annual updates published in a readily available source, and suitability for population-based projections (e.g., per capita basis).

[28] Previously, national solid waste generation has been estimated from population by application of a constant generation rate per capita [*Bingemer and Crutzen*, 1987] or from Gross Domestic Product (GDP) [*Richards*, 1989]. The use of population alone is not sensitive to the ''affluence'' factor. Recently, *Mertins et al.* [1999] demonstrated that GDP per capita in 1995 for EU countries was linearly correlated to municipal waste generation per capita (r^2 = 0.69). For studies of diverse countries spanning several decades, GDP is less attractive since the published data involve normalization to a chosen currency for changing base years. In addition, annual GDP per capita for the poorest developing countries can be elevated or depressed by external factors not directly related to affluence (e.g., international aid programs and monetary policies).

[29] A previous study focusing on thirteen OECD (Organization for Economic Cooperation and Development) countries [*Bogner et al.*, 1993] compared numerous demographic and economic indicators to per capita solid waste generation. All of the countries except one (Portugal) had >50% urban population. Using published United Nations (UN) and OECD statistics for the year with the most available data, 1980, that study concluded that energy consumption per capita was the most statistically significant per capita surrogate for solid waste generation (linear regression r^2 = 0.84). Energy consumption per capita (in units of kg coal equivalent per capita) is also expressed in similar units to annual solid waste generation (mass per capita). Other variables that were examined but with less significant linear or quadratic fits included: GDP per capita, energy production per capita, and several demographic and environmental variables that might be correlated to affluence (life expectancy, traffic density, infant mortality, and daily caloric intake). With respect to various refuse fractions, recognizing that 1980 predated the majority of local recycling programs, we also examined simple relationships between discards and production data for total metals, paper, plastics, and glass. The only significant linear correlation was between per capita paper discards and per capita paper production (r^2 = 0.66; n = 13), recognizing that paper constituted 18–35% (w/w) of total waste.

[30] For the current study, the energy consumption surrogate of *Bogner et al.* [1993] was further tested over multiple years and for multiple countries, including developing countries, by screening available national solid waste data and including only those data that were referenced to a specific year. Available data from 1975–1995 were composited. Then empirical relationships were developed to predict per capita solid waste generation based on the energy consumption surrogate. Using simple linear regression techniques, two empirical relationships were developed for per capita solid waste generation based on per capita energy consumption: a global relationship and a relationship for developing countries. Based upon the energy consumption data distribution compared to the UN categorization of ''developing'' countries, the distinction between developed and developing countries was arbitrarily set at a per capita energy consumption of 1500 kg coal equivalent per annum (KCEPA) (one KCE is equal to 29.31 GJ). The poorest developing countries with per capita energy consumption <100 KCEPA were normalized to 100 KCEPA as a minimum value. Annual per capita solid waste generation for each country was calculated from the surrogate relationship for 1980–1996, using either the global relationship for developed countries or the developing country relationship. We used commercially available data for 1980–1996 on total annual energy consumption for each country in British Thermal Units (BTUs) from the *International Energy Agency* (*IEA*) [2000] matched with total and urban population data for the same period from the *United Nations Food and Agriculture Organization* (*U.N. FAO*) [1998]. Total population was used for developed countries and urban population alone was used for developing countries, recognizing that most rural solid waste in developing countries is not landfilled. The resulting annual per capita waste generation for each country during 1980–1996 was used as the basis to estimate landfill CH_4 emissions.

[31] Some preliminary calculations for 5-year intervals, rather than annual estimates, were previously presented in a conference paper [*Bogner and Matthews*, 1999]. However, we have since found discrepancies between the per capita energy consumption data previously published in United Nations (UN) Statistical Yearbooks [*U.N.*, 1983, 1988, 1993, 1997] and calculated per capita energy consumption using raw data now available electronically [*U.N. FAO*, 1998; *IEA*, 2000]. For some developed countries, the latter were 30–50% higher; thus the regression equations herein differ from those presented previously.

3.3. Scenarios for Historic Emissions

[32] Four scenarios were developed (Table 1). First, using equation (3), annual emissions were calculated for each country using the energy surrogate and a modified IPCC methodology which assumed 0.50 dissimilated DOC and 10% CH_4 oxidation (Scenario A). Secondly, emissions were calculated using the energy surrogate with 0% oxidation (Scenario B). For scenarios C and D, two emissions estimates were developed using current IPCC default values for solid waste generated, % landfilled, and CH_4 emitted [*Meadows et al.*, 1996; *IPCC*, 1996]. For the higher IPCC scenario (Scenario C), the fraction DOC dissimilated was

Table 1. Summary of Scenarios A–D (This Study)[a]

Scenario	Waste Generation Per Capita	DOC_f[b]	OX[c]	Comments
A. IPCC surrogate A (recommended)[d]	varies with energy consumption; varies with time	0.5[e]	0.1[e]	lower CH_4 potential; 10% oxidation; lower emissions than B; total population: developed countries; urban population: developing countries
B. IPCC surrogate B[d]	varies with energy consumption; varies with time	0.5[e]	0	lower CH_4 potential; no oxidation; total population: developed countries; urban population: developing countries
C. IPCC default	constant	0.77	0	very high CH_4 potential; no oxidation; high emissions; total population (all countries)
D. IPCC revised[f]	constant	0.5[e]	0.1[e]	lower CH_4 potential; 10% oxidation; lower emissions than C; total population (all countries)

[a]See text for additional explanation.
[b]DOC_f, fraction of DOC dissimilated.
[c]OX, microbially-oxidized fraction of produced methane.
[d]Surrogate: per capita waste generation calculated using surrogate variable (per capita energy consumption).
[e]Recommendations of IEA/OECD/IPCC expert group meeting, Argonne National Laboratory, 1996 (T. Kerr, U.S. EPA, memo, 1997).
[f]Revised = alternative DOC and OX.

assumed to be 0.77 and methanotrophic oxidation was assumed to be zero (OX = 0), corresponding to values used by *Bingemer and Crutzen* [1987] and contained in the original IPCC default methodology. As discussed above, the 0.77 value is based upon an equation for optimized low solids anaerobic digestion and is too high for non-optimized high solids landfill systems under field conditions. The lower IPCC scenario (Scenario D) assumed that the fraction DOC dissimilated was 0.5, and methanotrophic oxidation was 10% (OX = 0.1), parallel to Scenario A using the energy surrogate. The values chosen for Scenarios A and D were based on a review of field and laboratory data incorporated in recommendations from an expert workshop to lower the dissimilated DOC and raise the fractional oxidation defaults (T. Kerr, U.S. EPA, memo, 1997). As also discussed above, laboratory studies indicate that the maximum carbon conversion for optimized landfill systems, equivalent to the fraction DOC dissimilated in equation (3), is approximately 0.25–0.50 [*Bogner*, 1992; *Barlaz*, 1998], with non-optimized field systems typically much lower [*Bogner*, 1992; *Bogner and Spokas*, 1993]. With respect to CH_4 oxidation, the 10% value is derived from a study by *Czepiel et al.* [1996a] in which field data and a seasonal climatic model were used to estimate an annual oxidation of approximately 10% at a New Hampshire landfill. Since the fraction DOC dissimilated is typically much less than 0.50, and CH_4 oxidation can vary from zero to more than 100% (oxidation of atmospheric CH_4), these are still conservative calculations from a regulatory perspective, since they overestimate the mass of CH_4 generated and emitted to the atmosphere.

[33] For all four scenarios, the per capita waste generation was multiplied by population to calculate annual national solid waste generation and, using the other factors shown in equation (3), to calculate annual CH_4 emissions from landfills. These factors were taken directly from *Meadows et al.* [1996] and from IPCC inventory documents. For Scenarios A and B, the fraction landfilled varied between 0.2 and 1.0. For Scenarios C and D, the IPCC national default values for kg solid waste landfilled per capita per day ranged from 0.2 to 0.6 for developing countries and from 0.4 to 1.7 for the developed countries of Europe, North America, Asia, and Oceania. In all scenarios, a single fraction DOC ranging from 0.08–0.20 (w/w) and a single MCF (CH_4 correction factor) ranging from 0.4–1.0 was applied to each country taken directly from IPCC documents. For developing countries in Scenarios A and B, it should be emphasized that urban population was used rather than total population to provide a more realistic estimate of the total mass of solid waste that is being generated and managed within the urban infrastructure. It is well known that rural areas in developing countries practice more dispersed types of waste disposal and recycling (including animal fodder) which would not be expected to generate significant quantities of CH_4.

3.4. Methodology and Data for Landfill Methane Recovery

[34] The mass of recovered CH_4 is the R term in equation (3). Starting with the first commercial U.S. recovery project in 1975, data were compiled from periodically published global reviews, corrected in some cases from corroborating sources or databases. These reviews and databases included U.S. and European sources [*Bogardus*, 1986; *Richards*, 1989; *Berenyi and Gould*, 1991, 1994; *Gendebien et al.*, 1991, 1992; *U.K. Department of Energy*, 1990; *Thorneloe and Pacey*, 1994; *Thorneloe et al.*, 1997; *McGuigan*, 1998; *Kruger et al.*, 1999; J. Bogner, unpublished 1978–1984 data consisting of U.S. recovery project summaries compiled by Argonne National Laboratory, U.S. Department of Energy, and the Governmental Refuse Collection and Disposal Association (GRCDA)].

[35] Separate linear regressions were fitted to data for the years 1975–1987 and 1987–1996 since projects from 1975

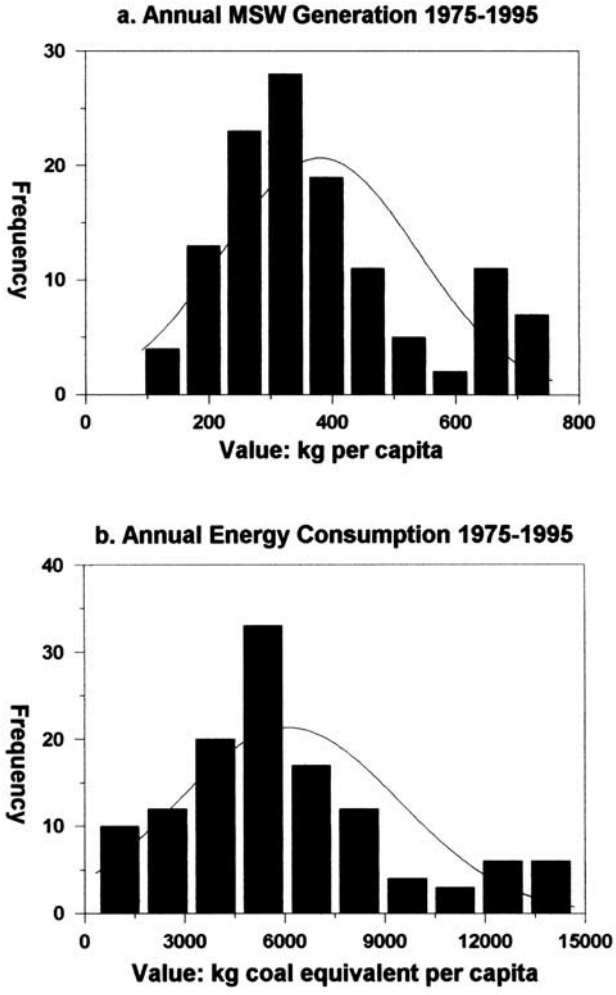

Figure 1. Histograms for (a) per capita solid waste generation and (b) per capita energy consumption. Composited data are for 1975–1995. Histogram for per capita energy consumption (Figure 1b) is limited to data matching Figure 1a.

into the early 1980s were concentrated in the United States, while European projects expanded greatly after the mid-1980s. For the years after 1990, a linear projection to 1996 was made, based on the 1987–1990 trend. *Meadows et al.* [1996], in the most recent global summary of commercial projects, compiled national lists containing the number of projects but did not tabulate the detailed recovery data from each project. In general, the recovery data are biased low because of a large number of uncounted projects which flare gas but do not fuel a commercial project.

4. Results and Discussion

4.1. Solid Waste Generation Using Energy Surrogate

[36] Figure 1 gives two histograms showing similar distributions for composited 1975–1995 per capita solid waste generation data and the matching data for per capita energy consumption. Figures 2a and 2b show relationships between per capita solid waste generation and per capita energy consumption. As discussed above, input data consisted of composited 1975–1995 solid waste data that were reliably referenced to a specific base year, matched with corresponding energy consumption data. Figure 2a is the global relationship ($r^2 = 0.51$), which excludes only Australia and New Zealand. The lowest values in Figure 2a were from developing countries while the highest values were from the United States and Canada. Figure 2b includes developing countries in Central America, South America, and Asia ($r^2 = 0.83$) and constitutes a subset of low values from Figure 2a. In this figure, note the steeper slope in comparison to the global relationship, indicating that per capita waste disposal can rise rapidly with increasing affluence, as measured by the energy consumption surrogate. Data from Australia and New Zealand were excluded from Figure 2a; they clearly constituted outliers, having higher per capita solid waste generation (450–700 kg per capita yr^{-1}) relative to lower per capita energy consumption (6000–8000 kg CE per capita yr^{-1}) than the rest of the world, which we attribute to their affluent but predominately rural economies. For the United States and Canada, which collectively constitute the high values in Figure 2a, a declining trend suggests that per capita solid waste generation can peak in developed countries and then decline in response to waste reduction and other initiatives.

[37] Most of the countries represented in Figure 2a have historically practiced controlled landfilling, collectively accounting for a large portion of the global CH_4 emission. Many European countries had fluctuating but generally rising per capita waste generation during this period. Examination of paired waste and energy data for developed countries grouped by years demonstrates that per capita solid waste generation also varies with per capita energy consumption for individual years; however, insufficient data were available to develop multiple relationships. In general, only 4–7 data points were available for each developed country for the 1975–1995 period. Some European countries, for example, France, when plotted separately, had regressions with the steeper slope characteristic of Figure 2b, but they were still within the overall data distribution shown on Figure 2a. Although data were limited, individual plots from several countries also demonstrated significant linear regressions between energy consumption per capita and solid waste generation per capita (r^2 = France 0.78; Italy 0.63; Spain 0.59; Austria 0.51; Finland 0.75; Japan 0.70; Portugal 0.92; Switzerland 0.64; U.K. 0.59). In addition, both annual increases and decreases in per capita solid waste generation were documented in data from several European countries; for example, many countries documented declining per capita waste generation between 1980 and 1985.

[38] Figures 3 and 4 compare the mass of landfilled solid waste according to Scenarios A and B (using energy surrogate) and Scenarios C and D (using IPCC default values), respectively. Results indicate that the energy surrogate approach better encompasses the variability of waste generation rates reflecting changes in the standard of living and urbanization. The use of total population for Scenarios C and D (Figure 4) indicates that roughly half of the global landfilled solid waste during 1980–1996 can be attributed

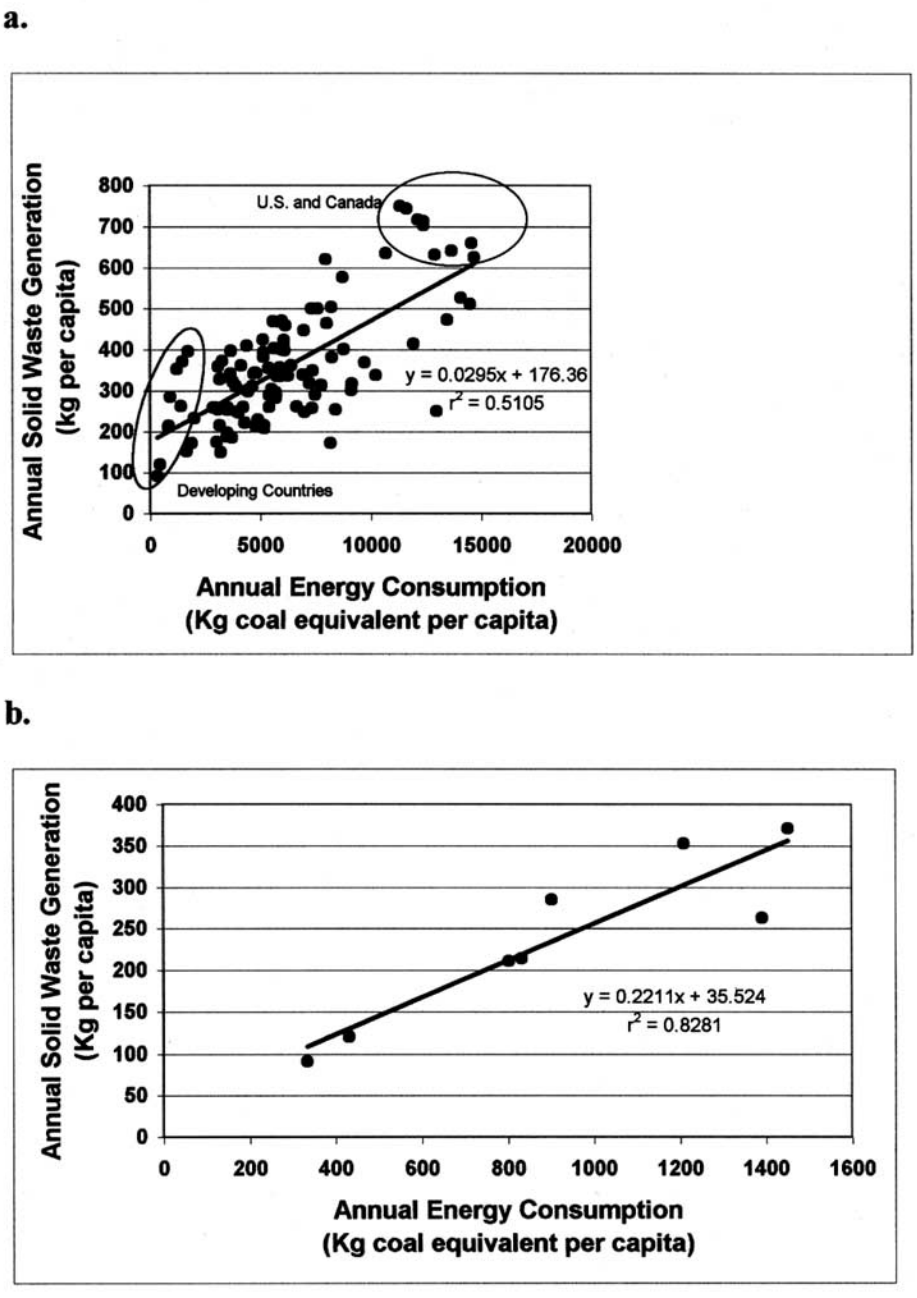

Figure 2. Relationships between per capita solid waste generation and per capita energy consumption. Data are composited from 1975–1995 [*IEA*, 2000; *World Resources Institute*, 1987, 1989, 1990, 1992; IPCC inventory documents, 1996; J. Bogner, unpublished data, 1996]. (a) Developed countries (except Australia and New Zealand) with per capita energy consumption >1500 kg coal equivalent per annum (KCEPA). Data are from Austria, Belgium, Canada, Cyprus, Denmark, Finland, France, Germany, Greece, Hong Kong, Iceland, Ireland, Italy, Japan, Korea, Netherlands, Norway, Poland, Portugal, Russia, Spain, Sweden, Switzerland, U.K., USA and developing countries listed in Figure 2b. Here n = 112. (b) Developing countries with per capita energy consumption <1500 KCEPA. Data are from Brazil, China, Costa Rica, Hong Kong, India, and Turkey. Here n = 8.

to Asia, mainly to China and India. In contrast, the majority of landfilled solid waste in Scenarios A and B (Figure 3) is from North America and Europe. The latter are more realistic scenarios because controlled landfilling with high rates of CH_4 generation was just beginning in Asian megacities during the 1990s. Moreover, developing landfills are concentrated in urban areas, consistent with the use of urban population alone for Scenarios A and B.

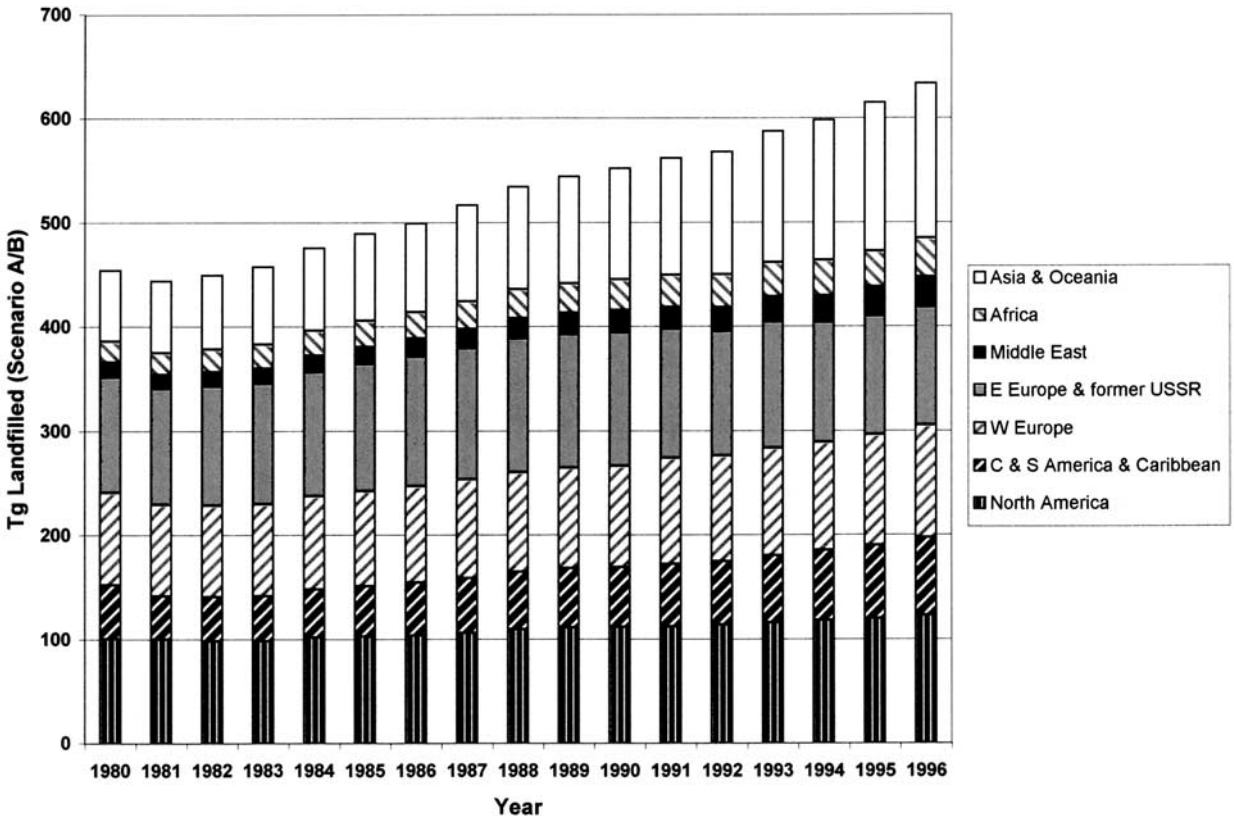

Figure 3. Landfilled solid waste for Scenarios A and B, using energy surrogate and either total population (developed countries) or urban population (developing countries). See Table 1.

[39] To provide an independent validation of the energy surrogate methodology for solid waste generation, calculated annual solid waste generation using the energy surrogate was compared to independent sets of recent 1990–1996 solid waste generation from the United States, Europe, and Japan. Sources for these data consisted of EU15 totals recently compiled by the European Environment Agency [*Brodersen et al.*, 2002], other national data recently compiled by the International Solid Waste Association [*Pasch et al.*, 1999], and U.S. data [*Franklin Associates*, 1999]. The resulting regression plot (Figure 5) indicates a high correlation between the predicted and actual solid waste generation ($r^2 = 0.93$). On the basis of the slope for the linear regression, the predicted data are about 70% of actual, with convergence at the lowest annual waste generation rates. For the United States specifically, annual solid waste generation using the energy surrogate was 9–27% lower than the Franklin numbers during the entire period of 1980–1996.

4.2. Global CH_4 Emissions From Landfills Inclusive of CH_4 Recovery (Scenarios A–D)

[40] Landfill CH_4 emissions for Scenarios A–D are shown in Table 2, which contains annual (gross) emissions and commercial CH_4 recovery for 1980–1996. The energy surrogate calculations (Scenarios A and B gross emissions) allow waste generation to vary with energy consumption while the IPCC default calculations (Scenarios C and D) assume constant waste generation rates varying with population alone. Scenarios A and D are comparable in terms of the fractions DOC dissimilated (0.5) and oxidized (0.1) and directly show the differences between an IPCC default calculation using total population (D) and an energy surrogate calculation using a combination of total and urban population (A).

[41] The two scenarios using the surrogate (A and B) indicate lower emissions than the IPCC default scenarios (C and D). Scenario A has the lowest emissions of 17–21 Tg during 1980–1996 while Scenario C has the highest emissions of 48–57 Tg during the same period based on unrealistically high DOC dissimilation. For developed countries only in Scenarios A and B, the emissions estimates may be biased low since waste generation is predicted by the energy surrogate calculation at about 70% of actual (Figure 5). However, compared to actual field conditions, scenarios A and B estimates would still tend to overpredict CH_4 generation and emissions because fractional DOC dissimilation under field conditions will be less than 0.5 and annual CH_4 oxidation, especially in warmer climates, will be greater than 10%.

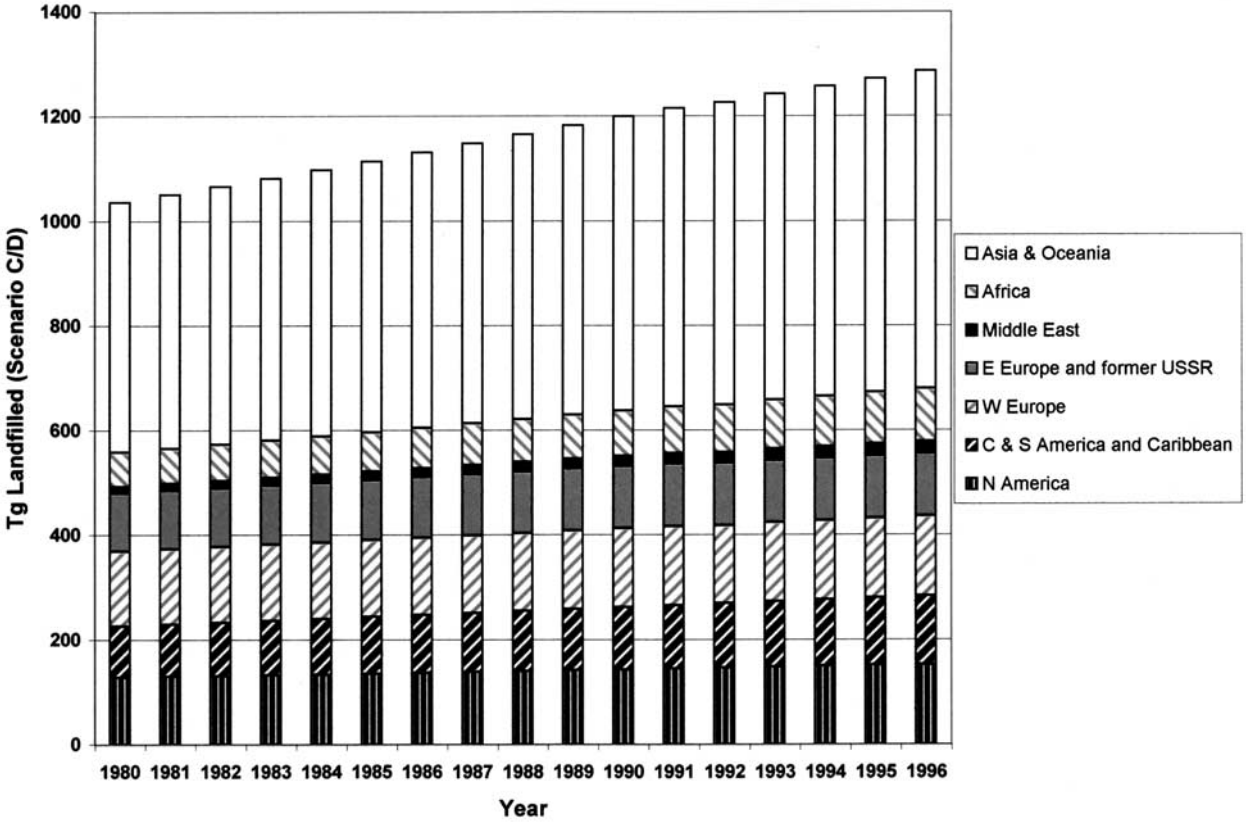

Figure 4. Landfilled solid waste for Scenarios C and D, using IPCC default values and total population. See Table 1.

[42] Emissions from Australia and New Zealand for Scenarios A and B were based on the linear regression shown in Figure 2a and included in the Table 2 totals, even though these countries constituted outliers as discussed above. These countries together account for only ~1% of the global solid waste generation and ~2% of the global landfill CH_4 emissions. For the Asia and Oceania region specifically, Australia and New Zealand totaled only ~4–5% of the solid waste generation but ~16–22% of the landfill CH_4 emissions. Thus use of the energy surrogate for Australia and New Zealand will not greatly impact global totals but would affect regional estimates.

[43] Considering both the total emissions in Table 2 and the regional variability in solid waste generation shown in Figures 3 and 4, it can be argued that Scenarios A and B, both using the energy surrogate, show trends which are more realistic than Scenarios C and D. Scenarios C and D indicate increasing emissions during the 1980–1996 period whereas Scenarios A and B indicate both increasing and decreasing trends. Globally, Scenarios A and B decline in the early 1980s, then increase to 1991, decline in 1992–1993, and then increase again in 1994–1996. These can be linked to a modeled decline in waste generation in North America in the early 1980s during an economic downturn and a decline in Europe in the early 1990s attributable to the economic situation in the former USSR. Considering the rapidity with which people's waste disposal habits adjust to changing economic conditions, these are more realistic scenarios than the Scenario C and D projections which constantly increase with total population. Of the four scenarios, we would favor Scenario A because it encompasses changing economic conditions and includes CH_4 oxidation. Both Scenarios A and B suggest that the decline in landfill CH_4 emissions of <1 Tg would have a negligible impact on the declining growth rate of atmospheric CH_4 after 1990.

[44] For commercial CH_4 recovery, global historical trends and sources of data are shown in Figure 6; annual totals are given in Table 2. Input data for Figure 6 consisted of published global reviews, corrected in some cases from other sources or databases. As discussed above, separate linear regressions were fitted to data for the years 1975–1987 and 1987–1995 (Figure 6a). The justification for two regressions is that the projects from 1975 into the 1980s were concentrated in the United States followed by a burst of European projects after the mid-1980s. Thus Figure 6a represents trends in commercial recovery of landfill CH_4 both during an earlier period (1975–1987) dominated by

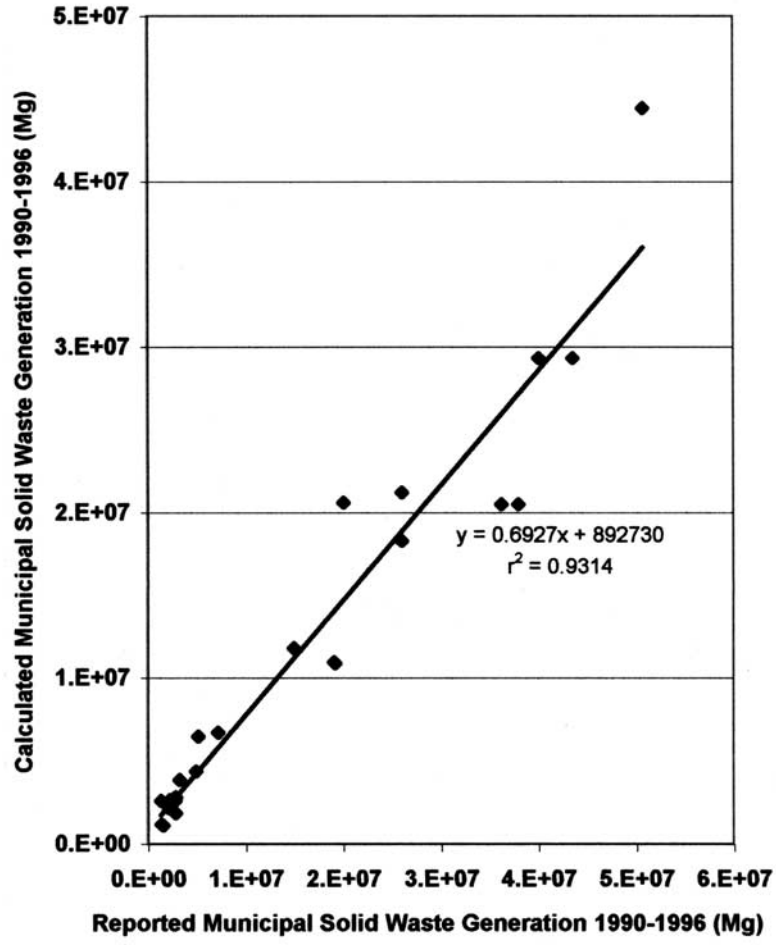

Figure 5. Predicted versus reported solid waste generation for EU15 countries, other European countries, United States and Japan for 1990–1996 [*Brodersen et al.*, 2002; *Pasch et al.*, 1999; *Franklin Associates*, 1999]. Predicted solid waste generation for energy surrogate Scenarios A/B use regression equation in Figure 2a.

U.S. projects (1975–1987) and for the period after 1987. For the years after 1990, a linear projection was made, based on the 1987–1990 trend.

[45] Figure 6b indicates the declining U.S. fraction of global production through 1996. Input data for this figure consisted of the projected trend through 1996 from Figure 6a and actual U.S. commercial recovery data. Post-1995, a large number of U.S. projects came online to take advantage of Section 29 (Internal Revenue Service) tax credits before they expired in 1998. Available data indicate that commercial U.S. production exceeded 4 Tg by 1999 (calculated from data given by *Kruger et al.* [1999]).

[46] For all scenarios in Table 2, note the increasing role of CH_4 recovery in limiting emissions, achieving a maximum of 16–18% in 1996 for the A and B energy surrogate scenarios. Moreover, the net CH_4 emissions for scenario A

Table 2. Annual Global Landfill CH_4 Emissions (Tg) During 1980–1996 for Scenarios A–D

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Emissions (gross)																	
Scenario A	16.9	16.6	16.7	16.8	17.4	17.8	18.0	18.5	19.0	19.3	19.4	19.6	19.3	19.6	19.8	20.2	20.7
Scenario B	18.7	18.5	18.5	18.7	19.3	19.7	20.0	20.6	21.1	21.4	21.6	21.8	21.5	21.8	22.0	22.4	23.0
Scenario C	47.7	48.2	48.8	49.4	49.9	50.5	51.1	51.8	52.4	53.0	53.6	54.2	54.4	55.1	55.6	56.2	56.7
Scenario D	27.9	28.2	28.5	28.8	29.2	29.5	29.9	30.3	30.6	31.0	31.4	31.5	31.8	32.2	32.5	32.8	33.1
Global recovery	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.9	1.3	1.6	2.0	2.3	2.7	3.0	3.4	3.8
Percent recovery A	1.1	1.3	1.6	1.8	2.0	2.2	2.4	2.5	4.8	6.6	8.4	10.1	12.1	13.7	15.4	16.8	18.2
Percent recovery B	1.0	1.2	1.4	1.6	1.8	1.9	2.1	2.3	4.3	5.9	7.5	9.1	10.9	12.3	13.9	15.2	16.4
Percent recovery C	0.4	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.7	2.4	3.0	3.7	4.3	4.9	5.5	6.1	6.6
Percent recovery D	0.6	0.8	0.9	1.0	1.2	1.3	1.4	1.5	3.0	4.1	5.2	6.3	7.3	8.4	9.4	10.4	11.3

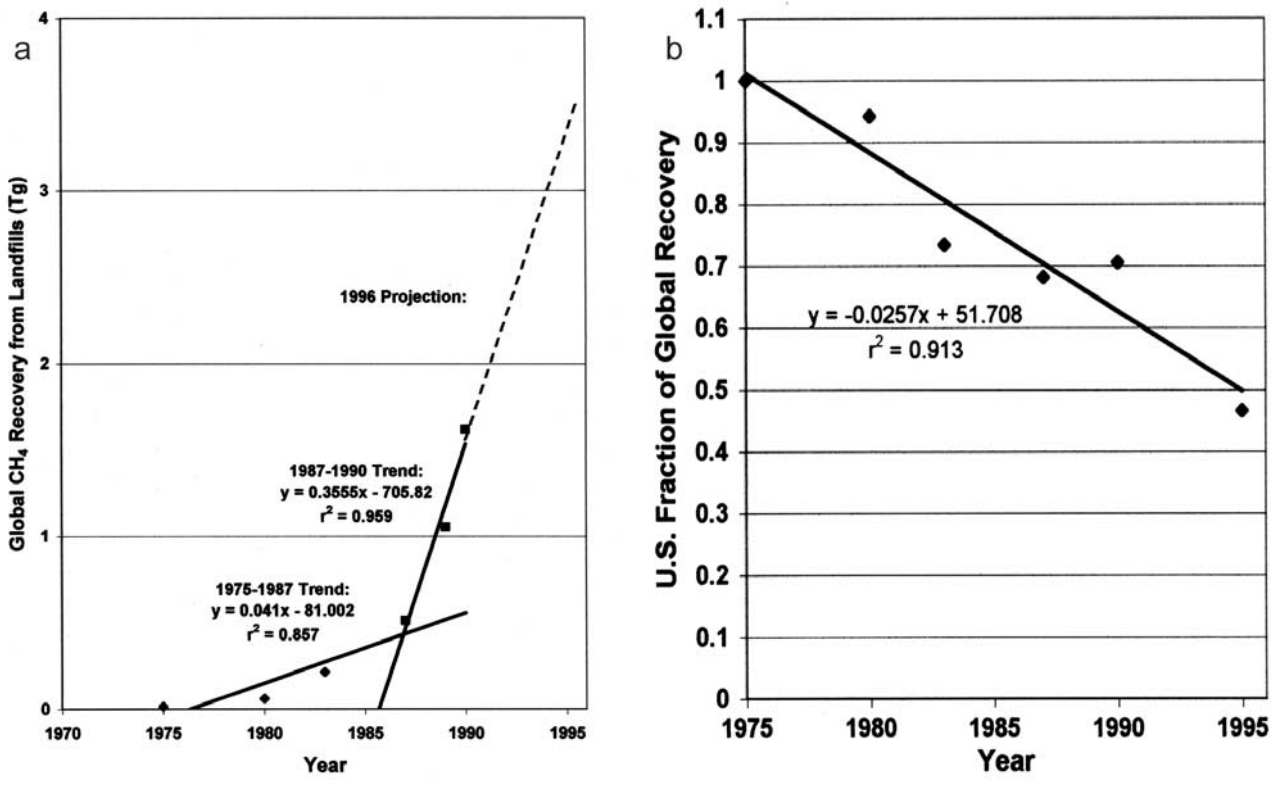

Figure 6. (a) Modeled trends for commercial landfill CH_4 recovery from 1975–1987 and 1987–1995 using available historical data. (b) Historical decline in U.S. fraction of global recovery through 1995 [*Bogardus*, 1986; *Richards*, 1989; *Berenyi and Gould*, 1991, 1994; *Gendebien et al.*, 1991, 1992; *U.K. Department of Energy*, 1990; *Thorneloe and Pacey*, 1994; *Thorneloe et al.*, 1997; *McGuigan*, 1998; *Kruger et al.*, 1999; J. Bogner, unpublished data]. Note that actual recovery is greater than shown because of flared gas which is not quantified.

have varied little during 1980–1996 because recovery has largely kept up with increases in gross emissions. It should be stressed that the recovery data and projections in Figure 6 and Table 2 are biased low because there are a large number of uncounted projects which flare landfill gas without fueling a commercial project. In the United States, and in many developed countries, quantification of flared CH_4 would increase national recovery by 50–100%. For Figure 6b, we excluded estimates of flared gas for the United States to be consistent with available data from other countries. However, *Meadows et al.* [1996] estimated total global recovery of almost 7 Tg yr^{-1} in 1995.

[47] Figure 7 compares independent 1990–1996 EU15 landfill CH_4 emissions recently reported to IPCC [*Ritter and Gugele*, 2001] with calculated EU15 emissions according to Scenarios A–D. The EU15 include Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the U.K. The national methodologies included a combination of Tier 1 and Tier 2 IPCC calculations. The EU15 numbers are net emissions (inclusive of CH_4 recovery) while the values shown for Scenarios A–D are gross emissions. The Scenario C values would approximate gross emissions for the EU15, and the differences of ~1.5–2.5 Tg yr^{-1} between Scenario C values and reported (net) EU15 values should approximate CH_4 recovery. This range is consistent with the *ATLAS Project* [1997] which indicated that EU15 commercial recovery in 1995 was ~1.5 Tg yr^{-1} while *Meadows et al.* [1996] estimated that EU15 recovery in 1995 was ~2.5 Tg yr^{-1}. If ~2 yr^{-1} are subtracted from the two energy surrogate scenarios (A and B), the net emissions from these scenarios would range from approximately equal to slightly below the EU15 numbers, indicating good comparison between the reported EU15 emissions and the two energy surrogate scenarios.

[48] In Figure 8, a similar comparison is made for the United States for 1990–1996, based on the three recent estimates of landfill CH_4 emissions, [*U.S. EPA*, 2002; *U.S. DOE/EIA*, 2001; *U.S. EPA*, 1999]. In this figure Scenario A–C estimates are lower than the three U.S. estimates. This is mainly attributable to (1) use of the higher Biocycle annual solid waste generation data [*Goldstein and Madtes*, 2001], which averaged 47% higher than the Franklin data [*Franklin Associates*, 1999] for the period 1988–1997; and (2) use of either a linear regression or FOD generation equation which yields high CH_4 generation rates. We would question the use of the higher Biocycle waste data, because it includes a large fraction of construction and demoli-

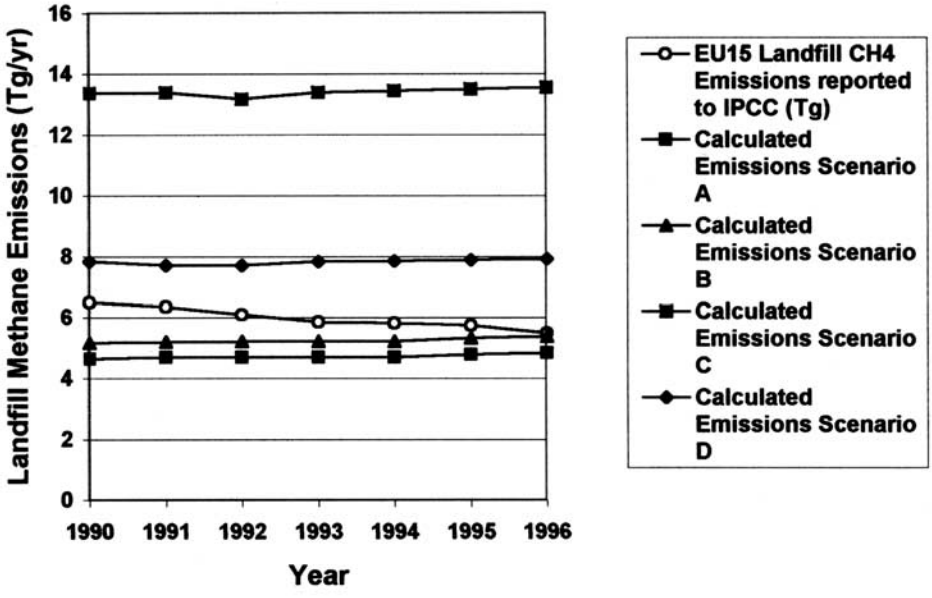

Figure 7. Comparison of Scenarios A–D for the EU15 to 1990–1996 EU15 landfill CH_4 emissions reported to IPCC [*Ritter and Gugele*, 2001].

tion(C&D) waste with low potential for CH_4 generation. Inclusion of C&D is also inconsistent with recent European Environment Agency practice, which tabulates the C&D separately from the "municipal waste," upon which emissions estimates are based (Figure 7). Moreover, based on the three U.S. estimates in Figure 8 compared to the Scenario A totals in Table 2, it is unreasonable that the gross U.S. emissions are 65–75% of the global total.

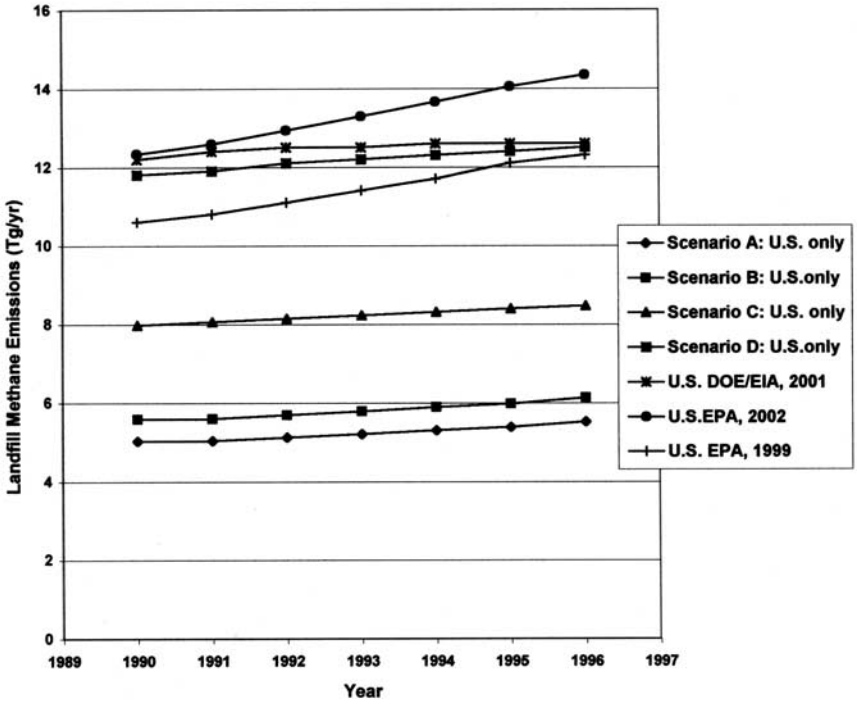

Figure 8. Comparison of Scenarios A–D for the United States to three 1990–1996 U.S. landfill CH_4 emissions estimates [*U.S. EPA*, 2002; *U.S. DOE/EIA*, 2001; *U.S. EPA*, 1999].

5. Conclusions and Future Perspectives

5.1. Landfill CH_4 Emissions: Recommendations for IPCC

[49] In this paper, we present and validate a methodology for historical landfill CH_4 emissions for 1980–1996 using a surrogate variable for per capita waste generation, i.e., per capita energy consumption. For the recommended scenario (A) during this period, gross landfill CH_4 emissions varied from 16.6–20.7 Tg with net emissions including recovery of 16.4–18.1 Tg. It is likely that the net emissions are biased high because of undercounting of recovery and underestimation of oxidation. It would not be unreasonable to add 50–100% to commercial recovery for most countries to account for flared CH_4. The alternative scenarios (B–D) all projected higher landfill CH_4 emissions, which are less realistic based on field and laboratory studies of CH_4 production from solid waste and CH_4 oxidation. The use of the energy surrogate lowers but does not greatly alter the overall magnitude of emissions compared to previous estimates; moreover, it better encompasses the variability of annual waste generation rates, reflects short-term changes in living standards and urbanization, and bypasses the problem of missing data.

[50] For national landfill CH_4 emissions reported annually to IPCC, we recommend Scenario A (energy consumption surrogate) for all developing countries where waste generation data are nonexistent or questionable, because it ties these calculations directly to energy data which are annually compiled, reported and updated. For developed countries, we strongly recommend that energy surrogate calculations be completed annually as a check on the range and temporal variability of estimated emissions, in parallel with the use of either an IPCC Tier 1 or Tier 2 calculation. Since we have shown that the surrogate variable reasonably predicts national solid waste generation for North America, Europe, and Japan, it would be relatively straightforward to develop scenarios for variable DOC, CH_4 yields, and percent oxidation to examine the sensitivity of national estimates to these variables using the surrogate variable for the base solid waste generation data. For Australia and New Zealand, specifically, which are outliers, the energy surrogate calculation should not be used for well-constrained regional estimates, but using this method for these countries in a global calculation does not substantially affect the results (1–2% of global emissions).

5.2. Conclusions, Data Needs, Trends, and Future Research

[51] For both developed and developing countries, the use of the per capita energy consumption surrogate for per capita solid waste generation provides a reliable methodology that facilitates annual updates using a consistent methodology and readily available data. This methodology is a significant improvement over ''rule of thumb'' estimates for solid waste generation, especially in developing countries. We suggest that the resulting CH_4 emissions estimates more accurately reflect short-term (e.g., annual) variations in emissions for developed and developing countries. Although the annual differences in landfill CH_4 emissions have negligible effect on short-term trends in atmospheric CH_4, the results will nevertheless be useful in combination with improved estimates for other CH_4 sources and sinks.

[52] The most critical data need is an updated global inventory for landfill CH_4 recovery, including both commercial utilization projects and flared gas. This number can be readily quantified with high accuracy via national survey data verified through government agencies. Moreover, since many developed countries are now mandating active landfill CH_4 recovery, it is important to compile reliable national databases so that greenhouse gas reduction targets can be accurately tracked.

[53] It is also important to consider trends in solid waste generation and management. For the future, controlled landfilling with CH_4 generation and emissions will be increasingly implemented in developing countries but will diminish in many developed countries. Thus it is important to have an improved methodology for estimating CH_4 emissions where reliable waste generation data do not exist. In rapidly growing ''mega-cities'' of developing countries, more engineered landfills will be developed to provide an affordable waste disposal solution that is more environmentally acceptable than current open dumping and burning practices. As urbanization increases in developing countries, improved solid waste management inclusive of landfilling will also be implemented for public health reasons. Urban dwellers produce more solid waste per capita than do rural inhabitants, and large amounts of refuse accumulating in areas of high population density are linked to vermin and disease [*Christensen*, 1989]. The process of converting existing open dumps to engineered landfills implies control of waste placement, compaction, and the use of cover materials. These practices will shift current production of CO_2 (by burning and aerobic decomposition during open dumping) to anaerobic production of CH_4.

[54] On the other hand, in the EU, a landfill directive (Council Directive 1999/31/EC) mandates that by 2016, a minimum of 65% of the biodegradable municipal waste produced in 1995 cannot be landfilled; rather, it will be diverted to incineration or mechanical and biological pretreatment before landfilling. However, since current landfill designs tend to retard natural infiltration and limit leachate generation resulting in lower rates of CH_4 generation, CH_4 production will continue at existing sites with declining rates for the next 2–3 decades with mandatory CH_4 recovery. All developed countries also practice increasingly higher rates of waste diversion via recycling and waste prevention.

[55] For the United States, Canada, Australia, New Zealand, and other non-EU developed countries with available open space, landfilling continues as a dominant disposal solution. Indeed, all of these countries are also considering various ''bioreactor'' landfill designs to compress the time period during which high rates of CH_4 generation occur. In these countries, decisions regarding waste management are made by local communities with limited financial resources who seek the least cost environmentally acceptable solution. In most cases, this means landfilling, except where adequate open space is not available. In the United States, by court decree, the interstate movement of waste to large regional landfills cannot be restricted.

[56] There are a wide variety of country-specific differences with respect to economic and regulatory incentives for commercial landfill CH_4 recovery. In the U.K., for example, the Non Fossil Fuel Obligation (NFFO), requiring a portion of electrical generation capacity from non-fossil sources, provided a major incentive for landfill-CH_4-to-electricity projects during the 1980s and 1990s. France has many projects which flare gas but limited on-site electrical generation because of low interest from the national electrical utility, EDF (Electricité de France). Some EU15 countries such as the Netherlands are currently mandating CH_4 recovery at all existing landfills. In the United States, which individually recovers more landfill CH_4 than any other country, more than 50 projects came on line in 1998, just before the expiration of Section 29 (Internal Revenue Service code) tax credits. It is anticipated that landfill CH_4 recovery will increase significantly in both the developed and developing countries of Asia, South America, and Africa during the next two decades as controlled landfilling is phased in as a major waste disposal strategy.

[57] For landfill CH_4 emissions, it is important to separate science goals and methodologies from regulatory/political goals and methodologies. For example, it is important to identify and modify conservative regulatory models which overestimate landfill CH_4 emissions when attempting to compile more accurate global inventories for climate modeling purposes. To date, little work has been undertaken to incorporate field measurements of emissions and oxidation into regional estimates, or to quantify regional variations in emissions resulting from increasing population, increasing urbanization, changing waste disposal practices, and recovery of landfill CH_4.

[58] Herein we have developed tools for regional and global assessments of CH_4 emissions from landfills based on simplified assumptions. We anticipate revising these approaches as more data become available from international field and laboratory studies. More reliable strategies to integrate site-specific measurements into regional estimates are clearly needed to address short-term temporal variations in landfill CH_4 contributions to the atmosphere.

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